A Typology for C^2 Measures

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Abstract

Numerous measures of the C^2 structure have been developed. The goal is to develop a small meaningful and predictive set. Work in this area, however, has been hampered by a lack of a standard categorization schema. Such a schema is presented herein. This schema is based on the recognition that many aspects of C^2 structures can be represented as graphs.

1. **Introduction and Motivation**

Measuring and monitoring the C^2 structure requires attendance to numerous aspects of the structure. Decades of research have been spent in an attempt to develop a small set of meaningful and predictive measures. The result has been a plethora of measures ranging in usability, predictability, and meaningfulness. Often, multiple measures have been developed for the same underlying construct - such as span of control. Currently there does not exist a commonly accepted taxonomy for classifying C^2 architectures or a commonly accepted set of measures. Within the organizational theory community debate rages over whether or not such a taxonomy, and the associated measures, is possible, let alone useful. McKelvey [1982] sees a need for such a taxonomy. Some schemes for classifying organizations have been based on strategy [Romanelli, 1989] or product service [Fligstein, 1985]. Other researchers have classified organizations using multiple dimensions, such that one or more measures are used to place an organization along that dimension. For example, Aldrich and Mueller [1982] categorize organizations using the dimensions of technology, coordination, and control.

There are three core difficulties with the standard approach. First there is no unifying scheme for categorizing, contrasting and comparing such measures. Such a unifying scheme would also

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benefit the field by enabling the identification of areas where no measures have been developed. Second, there is no common underlying representation of C^2 data. Such a common representation scheme would make it possible to formally define what measures are possible, ensure comparability of measures in lab, field, live-simulation, and computer simulation data gathering exercises. And third, there is no basis for determining the robustness of these measures and their extensibility to different size groups. Without such a basis the usability, predictability, and meaningfulness of measures is difficult to discern mathematically.

2. **Meta-Matrix Representation for C^2 Structures as Typology**

In contrast with these previous efforts, what we wish to suggest is a graph theoretic approach to this problem. Specifically, we conceptualize organizational structure, i.e., the C^2 architecture as a set of interlinked graphs. The result is a typology for measuring and monitoring the C^2 structure based on a network approach to organizational units. We illustrate this approach using a simple structure (shown below), data from an A2C2 experiment on C^2 adaptability, and data from a computer-simulation experiment on C^2 adaptability. A graph theoretic approach to organizational measurement is not in itself new. Numerous organizational researchers use network measures to address organizational issues.

Indeed, numerous network measures have been developed [Wasserman and Faust, 1994], some of which were developed particularly to address organizational issues [Krackhardt, 1994; Lin, 1994]. However, a common failing of these measures is that they assume that the organizational structure is adequately described in terms of the personnel and the relations among them. If this were the case, then organizations with identical authority structures should behave identically; but, this is assuredly not the case. In contrast to this personnel only approach, we argue that, at a minimum, personnel, resources and tasks, and the connections within and among each of the sets of components must be considered. Further, we use the term resources broadly to include both physical artifacts or assets and knowledge.

To illustrate our argument we use the hypothetical structure shown in Figure 1. Here there are 5 personnel (the circles), 4 resources (2 aircraft and 2 ships), and 8 tasks. These tasks need to be done to complete the mission. The lines indicate the relations among personnel, resources and tasks.

Representing the C^2 architecture as a set of matrices linking personnel, resources, and tasks results in a meta-matrix with 6 sub-matrices. These 6 sub-matrices are shown in table 1: networks, capabilities, assignments, substitutes, needs, precedence. This meta-matrix serves as a typology for classifying all network based measures of organizational structure. This typology, by including substitutes, extends the earlier PCANS framework defined by Krackhardt and Carley [1998]. Known measures of organizational design, such as unity of command, can be categorized by which of these matrices they take into account. An illustrative measure or two for each matrix is listed in each cell. A review of network based measures of organizational structure reveals that most such measures utilize the matrix in only one cell in the meta-matrix. Indeed, most such measures consider only the personnel-personnel cell. Such measures are typically referred to as social network measures. A survey of known measures indicates that few exist which consider substitutes, at least directly. To the extent that social network measures assume that all nodes are of the same type and that the matrix is square, these measures can be applied to either substitutes or precedents, albeit with some need for re-interpretation. For the network sub-matrix measures such as density, hierarchy, and graph connectivity are available for characterizing graphs [Krackhardt, 1994; Wasserman and Faust, 1994]. While most of these measures can be applied to any data that can be represented as graphs, whether or not they are meaningful depends on what data it is. For example, while span of control make sense if the graph represents the command structure it makes less sense if the graph represents the precedence ordering among tasks. These relations may be directed or not.

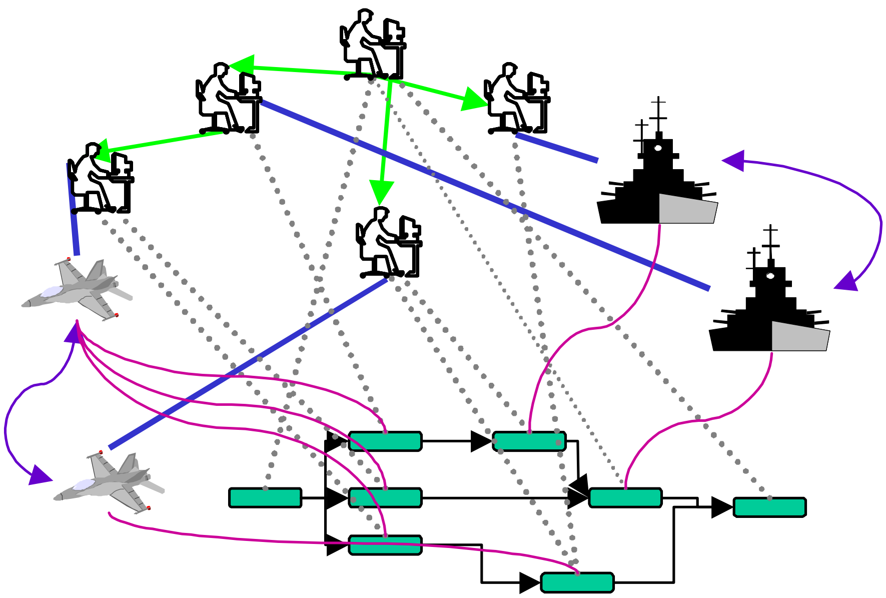

Figure 1. Hypothetical Structure for Illustration

There are a few measures that have been developed for networks with two types of nodes (such as the capabilities, assignments, or needs matrices). However, there are substantially fewer of these and they have been less explored. There are also more detailed measures of process that take multiple sub-matrices into account and most theories of organizational performance, adaptation or change implicitly or explicitly rely on the interactions among two or more sub-matrices. Further, we can compare and contrast the C^2 structures of different organizations by comparing and contrasting their meta-matrices.

	Personnel	Resources	Tasks
Personnel	Networks 5 size 2 span of control	Capabilities 1 coverage	Assignments 1.8 workload
Resources		Substitutes 0 unique	Needs 1.5 usage
Tasks			Precedents 0.25 complexity

Table 1. Meta-Matrix Representation

We can go from an organizational description and data on a unit (such as a team, group, task force, or organization) to a matrix by uniquely identifying each personnel, resource and task and then noting with a 1 that they are connected (i.e., a line occurs in the illustrative structure) and a 0 otherwise. This matrix representation scheme defines a common basis for the comparison of measures. Representing the C^2 architecture in this way enables organizational theories to be contrasted, compared, and given more precise form [Krackhardt and Carley, 1998]. This representation can be used for representing all C^2 structures, irrespective of the source of the data. For example, hypothetical structures, such as the illustrative structure shown in Figure 1 can be represented (see Table 2). We can represent the C^2 structures of organizations that are simulated, such as those simulated using ORGAHEAD, using this framework. We can represent the C^2 structures of organizations used in laboratory experiments using this framework. For example, in the next section we represent the C^2 structures used in the 4^{th} A2C2 experiments at the Naval Post Graduate School and corresponding computer-based simulation experiments on adaptive architectures. In principle, HR records, the organizational chart, the organization's communication network, data from surveys, and so forth can be used as well to fill in this data-structure.

	Personnel	Resources	Tasks
Personnel	01110		0000
	10000011		
	00001		0010
	01000000		
	00000		0100
	00001100		
	00000		0010
	00001000		
	00000		1000
Resources	00110000		
	-------	0100	01110000
	-------	1000	00000100
	-------	0001	00001000
	-------	0010	00000010
Tasks			
	-------		-------
	01110000		
	-------		-------
	00001000		

Table 2. Illustrative Structure as Meta-Matrix

When there is more than one type of relation in a cell then multiple matrices exist in that portion of the sub-matrix. These can be combined into a single weighted matrix or treated as multiplex relations. For example, in the case of the networks cell, we can imagine both authority relations (who reports to whom) and communication relations (who can send messages to whom).

3. **Utilizing the Typology**

Measures defined using this representation scheme way were collected in both laboratory and computer-based simulation experiments. The human experiments were conducted at the Naval Post Graduate School as part of the A2C2 project. Portions of the C^2 structures from the 4^{th} experiment are listed in tables 3,4 and 5. Each of these C^2 structures, i.e., their meta-matrix representation, were then used as input to various organizational performance computer models, such as CONSTRUCT [Carley, 1990; 1991] and ORGAHEAD [Carley & Svoboda, 1996; Carley & Lee, 1998]. Using the common representation afforded by the meta-matrix enabled us to compare the predictions of the computer-based simulation model with the human laboratory data.

	Personnel		Resources
	Authority	Communication	
Personnel	1 1 1 0 0 0	1 1 1 0 0 0	1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	1 1 0 0 0 0	1 1 1 0 0 0	0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	1 0 1 1 1 1	1 1 1 1 1 1	0 0 0 0 0 0 0 0 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0
A06	0 0 1 1 00	0 0 1 1 1 1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0
	0 0 1 0 1 0	0 0 1 1 1 1	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 1 0 0 1	0 0 1 1 1 1	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1
Personnel	1 1 1 1	1 1 1 1	1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1
	1 1 0 0	1 1 1 1	0 1 1 1 1 1 1 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	1 0 1 0	1 1 1 1	0 0 0 0 0 0 0 1 0 0 1 1 0 0 0 0 1 0 1 1 1 0 0 0
A14	1 0 0 1	1 1 1 1	0 0 0 0 0 0 0 1 0 0 0 0 1 1 1 1 1 1 1 0 0 0 0 0
Personnel	1 1 1 1 0 0	1 1 1 1 0 0	0 0 0 0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	1 1 0 0 0 0	1 1 1 1 0 0	0 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	1 0 1 0 1 1	1 1 1 1 1 1	1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1 1
A16	1 0 0 1 0 0	1 1 1 1 0 0	0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 0 0
	0 0 1 0 1 0	0 0 1 0 1 1	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 1 1 1 0 0 0
	0 0 1 0 0 1	0 0 1 0 1 1	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 1 1 1 1 0 0 0 0 0

Table 3: Network and Capabilities sub-matrices for 3 C^2 structure for 4th A2C2 Experiment

These 3 structures differ in the networks, capabilities and assignments. In all cases the requirements (what resources are needed to do which tasks, table 4), the precedence (which tasks come before which, not shown), and the substitutes (not shown) are the same. Given these structures the performance and diffusion properties of the structures were examined.

	Resources
Tasks	0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0
	0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 1
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0
	0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0
	0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0
	1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1
	1 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0
	0 0 0 0 0 0 0 0 0 0 0 1 0 1 1 0 0 0 0 0 0 0 0 0
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0
	0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0

Table 4. Requirements sub-matrix for 3 C^2 structure for 4^{th} A2C2 Experiment

	Personnel		
	A06	A14	A16
Tasks	1 0 0 0 0 0	0 1 0 0	0 1 0 0 0 0
	0 1 0 0 0 0	0 1 0 0	1 0 0 0 0 0
	1 0 0 0 0 0	0 1 0 0	0 1 0 0 0 0
	0 1 0 0 0 0	0 1 0 0	1 0 0 0 0 0
	1 0 0 0 0 1	1 0 0 0	0 0 1 0 0 0
	0 0 1 0 0 0	0 1 0 0	1 0 0 0 0 0
	0 0 1 0 0 0	0 1 0 0	1 0 0 0 0 0
	0 0 1 0 0 0	0 1 0 0	1 0 0 0 0 0
	0 0 1 1 1 0	0 0 0 1	0 0 0 0 0 1
	0 0 0 0 0 1	1 0 0 0	0 0 1 0 0 0
	0 0 1 1 1 0	0 0 1 0	0 0 0 0 1 0
	0 0 1 1 1 0	0 0 0 1	0 0 0 0 0 1
	0 0 1 1 0 0	0 1 0 0	1 0 0 0 0 0
	0 1 0 0 1 0	0 1 0 0	1 0 0 0 0 0
	0 0 1 1 1 0	0 0 0 1	0 0 0 0 0 1
	0 0 1 1 1 0	0 0 1 0	0 0 0 0 1 0
	0 1 0 0 0 0	0 1 0 0	1 0 0 0 0 0
	0 0 0 0 0 1	0 1 0 0	1 0 0 0 0 0
	0 0 1 1 1 0	0 0 0 1	0 0 0 0 0 1
	0 0 0 0 0 1	1 0 0 0	0 0 1 0 0 0
	1 0 0 0 0 1	1 0 0 0	0 0 1 0 0 0
	1 0 0 0 0 1	1 0 0 0	0 0 1 0 0 0
	0 0 0 0 0 1	1 0 0 0	0 0 1 0 0 0
	0 0 0 0 0 0	0 1 0 0	1 0 0 0 0 0
	0 1 1 0 1 0	0 1 0 0	1 0 0 0 0 0
	0 1 0 1 1 0	0 1 0 0	1 0 0 0 0 0
	0 0 1 0 0 0	0 0 1 0	0 0 0 1 0 0
	0 0 1 1 1 0	0 0 0 1	0 0 0 0 0 1
	0 0 1 1 1 0	0 0 1 0	0 0 0 0 1 0

Table 5. Assignment sub-matrices for 3 C^2 structure for 4^{th} A2C2 Experiment

Given the networks and capabilities sub-matrices a measure of expected performance can be calculated. Expected performance given perfect communication and no unexpected events is shown on the right on Figure 2. All else being equal, simulation suggest that the 4 node structure, A14, is expected to be a high performer. However, in point of fact it is not the best performer. Actual performance data is shown on the left in Figure 2. So why is this? Further analysis reveals that in terms of information diffusion, that in A16 information should take the longest to diffuse on average. However, there is a striking difference in terms of whether that information is about the coordinating information or whether that information is about resources. In Figure 3 we see that while resource usage information is slow to diffuse in A16, coordinating information appears to diffuse rapidly. Note, the higher the time-to-diffusion the longer it takes team members to learn the information on average. This suggests that part of the bases for high performance is the robustness of this structure in facilitating the flow of information about what others are doing.

Actual Performance　　　　　　　　　　Predicted Performace

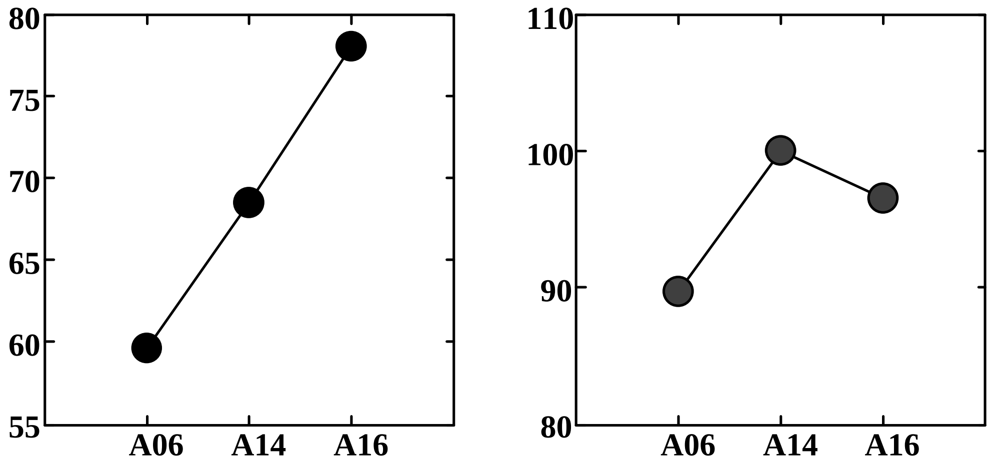

Figure 2. Actual and predicted performance.

Time to Diffusion

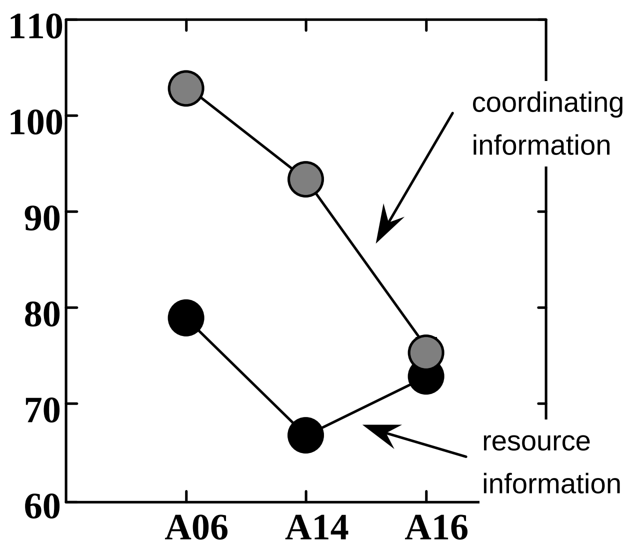

Figure 3. Predicted time to diffusion of coordinating and resource information.

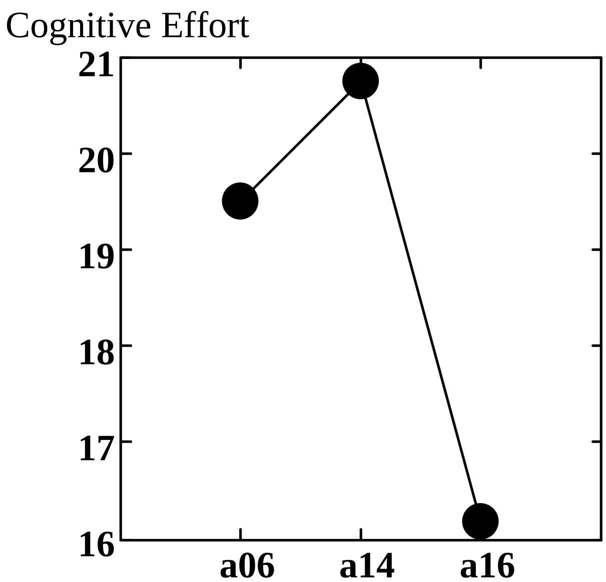

Figure 4. Cognitive effort of C^2 structures

A second, explanation of the relatively high performance of A16 has to do with cognitive effort. Cognitive effort can be measured as the average sum of the number of personnel, tasks and resources that each person in a structure needs to contend with. That is, given the meta-matrix, sum each row in personnel and average by the number of personnel. Doing this provides the information that in A14 and A06 individuals on average need to expend more effort than in A16. The more even spread of cognitive effort in A06 further degrades that structures performance, as the even distribution of cognitive effort drags every one down, rather than allowing a few to shine.

4. **Conclusion**

The proposed typology enables graph-theoretic based measures of C^2 structures to be contrasted and analyzed in a systematic fashion. Results indicate a dearth of measures that link more than one-submatrix. Attempts at predicting performance of organizations based on a single sub-matrix typically fail. Predictions, such as those herein, that are based on multiple sub-matrices at once fare better. Using this typology we defined the C^2 structure of three teams, examined in a laboratory setting. Use of the typology as a representation scheme enabled the three teams to be simulated. These simulations suggested that the reason for differences in performance had to do with the relative ability of information about what others are doing, versus what resources are needed for what through the structure defined by multiple sub-matrices.

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